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Highly Selective Halide Receptors Based upon Chalcogen, Pnicogen, and Tetrel Bonds

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ABSTRACT

The interactions of halides with a number of bipodal receptors are examined via quantum chemical methods. The receptors are based upon a dithieno thiophene framework in which two S atoms can engage in a pair of chalcogen bonds with a halide. These two S atoms are replaced by P and As atoms to compare chalcogen with pnicogen bonding, and by Ge which engages in tetrel bonds with the receptor. Zero, one, and two O atoms are added to the thiophene S atom which is not directly involved in the interaction with the halides. Fluoride is bound the most strongly, followed by Cl^-, Br^-, and I^- in that order. Replacing S by the pnicogen bonds of P strengthens the binding, as does moving down to As in the third row of the periodic table. A further large increment is associated with the switch to the tetrel bonds of Ge. Even though the thiophene S atom is remote from the binding site, each additional O atom added to it raises the binding energy, which can be quite large, as much as 63 kcal/mol for the Ge••F^- interaction. The receptors have a pronounced selectivity for F^- over the other halides, as high as 27 orders of magnitude. The data suggest that incorporation of tetrel atoms may lead to new and more powerful halide receptors.

INTRODUCTION

Amongst the pantheon of noncovalent forces, the H-bond is arguably the most widely famed, with a long and distinguished history of study, and an impressive list of processes in which it plays an essential role [1-3]. It has become increasingly clear that there are other bonds possible in which the bridging proton of the H-bond is replaced by an atom of several other groups. The halogen bond is a prime example [4-14]. Although the bridging halogen atom does not necessarily carry an overall partial positive charge as does the H-bond's proton, the electrostatic potential surrounding it is highly anisotropic. An equator of negative potential is capped by a positive region at its pole, directly opposite the R-X covalent bond. This positive pole can interact with an approaching electron donor in much the same way as can the H atom within the context of a H-bond. The H and halogen bonds share other features as well, such as the transfer of charge from the electron donor into the σ* antibonding R-H or R-X orbital, which in turn leads to a weakening of this covalent bond, and a red shift of its stretching frequency.

It has been shown that the halogen bond is competitive in strength with the more pedestrian H-bond, and can in fact exceed the latter. This strength, as well as other aspects of the halogen bond has led to its application in a wide range of chemistry and biology. For example, halogen bonding can assist in certain aspects of catalysis [15-18] or to amplify [19] the magnitude of a receptor's voltammetric responses for halide sensing over that of H-bonding analogues.

One of the more intriguing and potentially useful applications of halogen bonds is associated with the development of receptors that are highly selective for one anion over another [19-24]. In an early effort in this direction, the Beer group [25] found that substitution of H by Br enabled the consequent halogen bond to more effectively bind chloride. They later showed [26] receptors of this type could recognize both chloride and bromide ions, purely by virtue of halogen bonds, and an increased affinity over H-bonding analogues in a picket-fence scaffold [27] or rotaxane motif [28]. Chudzinski et al [29] obtained quantitative estimates of the contribution of halogen bonding to the binding of anions to bipodal receptors, along with noting a preference for halides over oxoanions. This group later [30] applied I halogen bonds to develop preorganized multidentate receptors capable of high-affinity anion recognition. Huber's group compared [31] entropic with enthalpic contributions to such binding. Halogen bonding exerts selectivity for bromide over chloride, or other anions in a set of tripodal receptors [32].

Our own group has engaged in several recent studies in this arena, where our quantum calculations have compared halogen with hydrogen-bonded receptors. Replacement of the H-bonding protons of bis-triazole-pyridine by halogen atoms [33] demonstrated that I-substitution yields the greatest binding enhancement with various halides. Adding positive charge to the receptor provided a further increment, and these receptors displayed a preference for F^- over other halides. This same fluoride preference was shown [34] by

a series of charged bis(triazolium) receptors, on which electron-withdrawing substituents have a greater influence for halogen bonding receptors than they do for H-bonding counterparts. A thorough examination of various different components from which halogen-bonding receptors might be built [35] confirmed the superiority of I as halogen, and showed that imidazolium outperforms triazolium, with benzene and dimethylnaphthalene as optimal spacers between the imidazolium rings.

The replacement of the bridging proton of H-bonds is not limited to halogens. A rapidly expanding literature has demonstrated the ability of chalcogen [36-44] and pnicogen [45-52] atoms to serve a similar function. More recently the tetrel family of atoms, headed by C and Si, have been added to this list. Research in this area [53-64] remains a bit more sparse, but there are indications that tetrel bonds can participate in reasonably strong noncovalent interactions.

Given the potential strength of chalcogen, pnicogen, and even tetrel bonds, it is natural to wonder if they can function as integral elements of selective halide receptors, in much the same way as H-bonds and halogen bonds. This curiosity was intensified by a very recent report [65] that a set of dithieno thiophenes can indeed bind anions quite strongly through the action of a pair of S••X^- chalcogen bonds. These strong interactions are all the more notable for the electric neutrality of these receptors, forgoing the strong Coulombic attractions of certain cationic receptors in the literature toward these anions.

This set of observations immediately poses a range of questions. How selective are such chalcogen-bond receptors to various anions? Can these receptors be modified so that the chalcogen bonds might be replaced by pnicogen or tetrel bonds, and if so, how do such substitutions affect their binding strength and selectivity? Is there a way to modulate these sorts of bonds by employing atoms from different rows of the periodic table? Can one fine-tune the selectivity even further by introducing perturbations on the chemical structure of each receptor that is separate from the atomic sites of interaction with the anion?

This work addresses these questions via quantum chemical calculations. This approach enables one to evaluate the most essential properties of each interaction, free of complicating factors such as interactions with surrounding molecules or the formation of trimers and higher aggregates. Geometries of interacting species can be known precisely, and the electronic structure can be analyzed to uncover the underlying causes of observed effects. The starting point for the receptors is the set of dithieno thiophenes studied previously by Benz et al [65]. To the thiophene S atom are added 0, 1, and 2 O atoms in turn which adjusts the electron-withdrawing capacity of the central thiophene ring. The two chalcogen-bond forming S atoms are replaced first by P so as to compare chalcogen with pnicogen bonding receptors. By then changing P to As, it is possible to examine the effects of going from a second to third-row pnicogen atom. The replacement of As by Ge then permits the formation of tetrel bonds as a mechanism for binding an anion. All receptors are combined with the set of four halides F^-, Cl^-, Br^-, and I^-, so as to examine issues of anion

selectivity. As such, this work represents the first assessment of the feasibility of using either pnicogen or tetrel bonds for the purpose of selective anion binding, and concludes that they both, and particularly the latter, offer superior opportunities in this regard.

COMPUTATIONAL METHODS

Calculations were carried out with the Gaussion-09 suite [66] of programs. The M06-2X DFT functional [67] was applied so as to ensure appropriate correlation and dispersion effects, along with the aug-cc-pVDZ basis set; the pseudopotential aug-cc-pVDZ-PP set was used for I to incorporate relativistic effects [68,69]. This basis set and functional have been applied previously to similar sorts of systems to good effect [14,33-35,70-75]. Relativistic effects are expected to be most significant for atoms below the third row of the periodic table. Minima on each potential energy surface were assured by the absence of any negative frequencies. In fact, for most dimers the smallest positive frequency was above 60 cm^{-1}; the smallest was 14 cm^{-1}. Binding energies were evaluated as the difference in energy between the optimized complex, and the sum of energies of the individually optimized component monomers. These quantities were corrected for basis set superposition by the Boys-Bernardi [76] counterpoise technique. Entropies and free energies were evaluated by standard thermodynamic formulae at 298 K. Equilibrium ratios between two different complexes with free energies G_1 and G_2 were computed as exp(-{G2-G1}/RT). Natural bond orbital (NBO) charge transfer energies [77,78] were derived from the NBO program incorporated within Gaussion-09.

RESULTS

Geometries and Energetics

The set of binding agents were based upon the dithienothiophenes used in the earlier work. One example of this molecule is shown in the upper part of Fig 1. This molecule is designated here as S3O0. Also considered were derivatives wherein one or two O atoms were added to the thiophene S atom. The addition of one such O atom would lead to S3O1, and two to S3O2, both pictured in Fig 1. As alternatives to the two S atoms that might engage in chalcogen bonds to an anion, the possibility of a pair of pnicogen bonds was considered by replacing these two S atoms by P, more specifically by PH. In addition to the corresponding P2SO0 shown in Fig 1, one or two O atoms were added to the thiophene S, yielding P2SO1 and P2SO2. The P pnicogen bond was compared to that from As in the next row of the periodic table, yielding As2SO0, As2SO1, and As2SO2, one of which is illustrated in Fig 1. Replacement of these two AsH groups by GeH_2 extended the study to tetrel bonds, via Ge2SO0, Ge2SO1, and Ge2SO2, the latter of which is displayed in Fig 1.

Each of the four halides F^-, Cl^-, Br^-, and I^- were allowed to form a complex with each of the binding agents, for a total of 48 different complexes. Geometries of a selection of the resulting complexes are

illustrated in Fig 2. With the exception of fluoride, the other anions engaged in symmetric complexes, with equal distances separating the halide from the two atoms to which it is noncovalently bonded in the complex. These interatomic distances are reported in Table 1 for all of the complexes, where a pattern becomes evident. The distances correspond to halide radii: F < Cl < Br < I, as one might expect. For a given halide, the distance contracts as one and then two O atoms are added to the thiophene S. Taking the pnicogen bond distances of P with Cl as an example, R(P••Cl) drops from 3.168 Å for P2SO0, down to 3.133 Å and then 3.072 Å as one and then two O atoms are added to S. With respect to the atom interacting with the halide, P engages in the longest bonds, and Ge the shortest, with little differentiation between S and As. However, it must be remembered that S and P are both second-row atoms, and As and Ge from the third row. The shortness of the tetrel bonds to Ge is thus particularly notable, given its large atomic radius. Likewise, the roughly equivalent bond lengths between S and As occur despite the larger size of As.

The geometric patterns of Fig 1 are reflected in the binding energies of the various complexes displayed in Table 2. F^- forms the tightest complexes, followed by Cl^-, Br^-, and then I^-. Just as the interatomic distance shrinks, so does the binding energy grow as O atoms are added to the thiophene S. This effect can be quite dramatic. X2SO2 is bound more strongly than is X2SO0 by some 13 kcal/mol for F^-. This difference is roughly 10 kcal/mol for the other three halides. Given their spacing from the actual sites of binding, the effects of these O atoms are rather remarkable.

There is a clear increase with binding energy in the order S < P < As < Ge, regardless of the halide. In more detail, the transition from second-row chalcogen to pnicogen bond (S→P) raises the binding energy by roughly 5 kcal/mol (8 for F^-). Within the framework of pnicogen bonds, the change from second to third row atom (P→As) yields a smaller increment of some 2 kcal/mol. A further enhancement is associated with the change from a pnicogen to a tetrel bond (As→Ge), both third row atoms. The latter increment amounts to 3-5 kcal/mol for the three larger halides, but as much as 10 kcal/mol for F^-. In a larger sense, the binding energies of these receptors with the halides are quite high. The maximum is associated with the binding of fluoride by the Ge receptors, between 50 and 66 kcal/mol. Even the much larger iodide anion binds strongly to these receptors, ranging from 7 to 24 kcal/mol.

It is commonly found that binding energies are substantially diminished when vibrational and entropic factors are included in the formulation. The Gibbs free energies of the association reactions reported in Table 3 do indeed indicate a weakening via less negative quantities. But this weakening is relatively modest, and the binding free energies are still quite substantial. The most strongly bound Ge2SO2-F complex is bound by ΔG= -55 kcal/mol, only a small reduction from ΔE of -63 kcal/mol. In fact, all

quantities in Table 3 are negative (with only one small exception) indicating a spontaneous association process.

If the objective of the receptor is to pull a halide out of aqueous solution, then it will be necessary to first break some of the HBs between the halide and water molecules. Given the geometries of these receptor-halide complexes, it is fair to say that two such HOH•••X^- HBs must be broken in favor of the two noncovalent bonds within the complexes. The last row of each section of Tables 2 and 3 contains the calculated ΔE or ΔG for the reaction between the indicated halide and a pair of water molecules, an example of which is displayed at the bottom of Fig 2. These values can be considered as somewhat inflated since the two water molecules form a third HB, with one another, in addition to the two OH•••X^- HBs of interest, but furnish a worthwhile point of comparison nonetheless.

Considering first the ΔE values in Table 2, in most cases the binding energy with the receptor is somewhat smaller than that with the pair of water molecules. One primary exception to this pattern are the Ge-bonds with fluoride. But also the Ge2SO2 complexes with any of the halides also tend to exceed the binding energy of the water pair. The competition shifts in favor of the receptors within the framework of ΔG. As is apparent in Table 3, regardless of the nature of the X atom, all X2SO2-halide binding free energies exceed that for the pair of water molecules. The same is true for the X2SO1 receptors, with the exception of X=S. Within the subset of weaker X2SO0 receptors, X2SO0 is favored over water only for X=Ge.

This competition for the halide between each receptor and water may perhaps be better viewed in the framework of the equilibrium constant for association with the receptor over the water. These equilibrium constants are exhibited in Table 4. The favorability of water is exemplified by values less than unity, common for many of the X2SO0 receptors. On the other hand, the preference for the receptor is most obvious for all three Ge receptors, which exceed 1 for all halides. This preference for receptor over water is most acute for fluoride, where equilibrium constants are quite large, as high as 5×10^{15} for Ge2SO2. The latter receptor is also quite strongly favored for the other halides as well, between 4×10^7 for I^- and 2×10^{10} for Cl^-.

Electronic Aspects

The obvious presumption is that these dimers are held together by noncovalent bonds of the chalcogen, pnicogen, or tetrel varieties. This supposition can be confirmed by examining whether certain criteria are met. From a geometrical perspective, such bonds have reasonably short contact distances. The R distances separating each halide from the relevant atom, displayed in Table1, easily meet this threshold. Secondly, the electron donor, in this case the halide, normally occupies a position roughly opposite one of the X-C bonds where X refers to the chalcogen/pnicogen/tetrel atom. Again this test is met easily. The θ(Hal••X-

C) angles in these complexes are all rather close to 180º, all within 16º of this angle, and many much closer than that.

Another common characteristic of such bonds resides in the NBO analysis of the wave function which provides localized orbitals. Within the context of these bonds, one typically sees a good deal of charge transfer from the lone pair(s) of the electron donor (the halide in this case) to the σ*(X-C) antibonding orbital. The energetic component of these charge transfers, E(2), is displayed in Table 5. These quantities are quite large, easily meeting the expectation for the presence of such bonds. Further reinforcing this notion, there is a clear correlation between the magnitude of E(2) and the binding energies in Table 2. For example, E(2) grows from left to right, as more O atoms are added to the thiophene S atom, and follows the same patterns as the energy, viz. $F^- > Cl^- > Br^- > I^-$, and S < P < As < Ge. It should be added parenthetically that the particularly large values for some of the fluoride complexes are a result of their asymmetry which place the F^- quite close to one of the X atoms of the receptor. It should be stressed that the E(2) charge transfer energies are not the only factor in the binding of the halides, as the binding energies do not strictly correlate with E(2) in a linear fashion. For example, E(2) climbs quite slowly as the number of O atoms increases from 0 to 1 to 2, in contrast to the much steeper ascent of the binding energies in Table 2.

As electron density flows into the σ*(X-C) bond, one would anticipate a weakening of this bond, and its resulting lengthening. This is indeed the general case in bonds of this type, and the systems studied here are no exception. Nearly all of the bond length changes in Table 6 are positive, indicating a lengthening. And these bond stretches parallel not only the charge transfers into the σ*(XC) antibond, but also the binding energies. Unlike the latter two quantities, however, Δr is not very sensitive to the number of O atoms on thiophene S, but there is a heightened sensitivity to the identity of the X atom. The bond stretch grows very quickly in the S < P < As < Ge sequence. The largest stretch occurs for the Ge••F^- complexes, as much as 170 mÅ. Even ruling out such asymmetric dimers, this stretch reaches 55 mÅ for the complexes of Ge with Cl^-. These stretches are all the more notable in view of the rigidity of the rings in which these atoms find themselves.

A typical observation in noncovalent bonds such as those studied here is that the molecular electrostatic potential surrounding the electron acceptor contains a region of positive potential pointing toward the approaching electron donor. The molecular potentials of some of the receptors are presented in Fig 3, where blue colors indicate the most positive regions, and red the most negative. With respect to the structures of the complexes formed here, attention is focused on the region between the two X atoms, where the halide will position itself. The figure indicates this region is bluer (more positive) for S3O0 as

compared to P2SO0; the change from As2SO0 and then to Ge2SO0 shows little variation. As O atoms are added to the Ge receptor, this positive blue region gets very much enhanced.

The positive potential can be quantified by considering the potential at a particular point. $V_{s,max}$ refers to the maximum of the MEP on a surface corresponding to an isodensity of 0.001 au. These quantities are listed in Table 7 for all 12 of the receptors. In line with their visual representations in Fig 3, there seems to be little variation between the S, P, and As receptors, but a significant increment in transitioning to Ge. Also consistent with Fig 3 is the strong increase of $V_{s,max}$ as more O atoms are added to the thiophene S atom. One may conclude that there is a certain degree of correlation between the binding energies and the intensity of the positive potential, i.e. the sigma hole, but this correlation is far from perfect. The only marginal dependence of the binding energy upon the MEP is not surprising in view of the addition of an anion to each receptor that is expected to introduce major perturbations in the isolated molecule.

DISCUSSION

There are a number of trends in the data reported here that are consistent with prior findings, as well as expectations. The diminishing charge density leads naturally to the $F^- > Cl^- > Br^- > I^-$ binding strength order of the anions. A good deal of prior work has shown that the lower electronegativity and greater polarizability as one moves down a column in the periodic table leads to stronger binding with an electron donor, consistent with the distinction between the P and As pnicogen bonds noted above. The data also fit the pattern that stronger binding correlates with shorter distances, as well as certain electronic features such as a greater degree of charge transfer, and the consequent stretch of the X-C bonds into which electron density is being deposited into the antibonding orbital.

On the other hand, there are a number of unexpected and even striking conclusions arising from these calculations. For one thing, the pattern of sharply increasing binding energy as one transitions from a chalcogen to a pnicogen, and thence to a tetrel bond is perhaps surprising. These changes are neither small nor subtle. There is as much as a 10 kcal/mol increase in binding energy from As to Ge, even though both atoms lie in the third row of the periodic table. A rise of up to 8 kcal/mol accompanies the transition from the chalcogen S to the pnicogen P, again with both atoms lying in the same row. This result differs from an earlier set of calculations [60]. A recent comparison of tetrel vs halogen bonds [64] yielded mixed results which depended upon the particular electron acceptor.

Also dramatic is the strength of some of these bonds, with binding energies as large as 63 kcal/mol. Past study of tetrel bonds suggest much smaller values in the context of neutral pairs [54,61,62,79,80] even when the fourth row Sn atom is involved [81,82]. Enhancing the electron-accepting ability of a tetrel atom by appending a metal cation [83] raises its binding strength, but only by up to 4 kcal/mol. If one allows for interactions with anionic halide, there are still few such interactions that approach the levels seen here. For

example, a fluoride binds to a C atom attached to three strongly electron withdrawing F atoms [84] by only 10 kcal/mol. The interaction energy [64] of F^- with CF_4 is only 6 kcal/mol, increasing up to 13 kcal/mol for CH_3F; tetrel bonds with chloride are weaker. When four F atoms are attached [55] to Si, its interaction energy with Cl^- is only 25 kcal/mol; this quantity rises to 41 kcal/mol when the Si is replaced by Ge. This latter value is comparable to the binding energy of the Ge2SO2 complex if the latter is cut in half, to account for the presence of two formal Ge-bonds in the receptor-halide complex.

The strengths of some of these interactions are underscored by a direct comparison of the binding energy of each of the various halides with a pair of water molecules, to replace the two noncovalent bonds in each complex. One might normally expect that a pair of OH••X^- ionic H-bonds ought to overwhelm the binding to a receptor which incorporates a pair of chalcogen, pnicogen, or tetrel bonds. Indeed, the complex with the pair of water molecules contains a separate HB between the two water molecules which would exaggerate the total binding energy of this complex. And in fact, the pair of water molecules is preferred over some of the weaker receptors considered here, e.g. those involving the chalcogen bonds of S. But importantly, there are a number of receptors which bind the halide more strongly that does the pair of water molecules. For most of the halides, F^- as an example, binding to the receptor is clearly preferred for Ge2SO2, Ge2SO1, and As2SO2, while Ge2SO0, As2SO1, and P2SO2 bind with equal strength. When one considers free energy, as opposed to simply ΔE, the preference switches even more strongly toward the receptors. All three of the Ge receptors, the O1 variants of As and P, and even S3O2 are preferred to the water pair. This preference for the receptors has major implications for the partitioning of the halides between the receptor and aqueous solution. The equilibrium ratio can be as large as 5×10^{15} for F^- and the Ge2SO2 receptor, but this same receptor is preferred over water by at least 4×10^8, in this case for Br^-.

A highly desirable characteristic of halide receptors is selectivity of one halide over another. By comparison of the binding free energies of the various receptor/halide combinations in Table 3, one can calculate the equilibrium ratio of one halide over another for a given receptor. The preference for F^- over the various halides, exhibited in Table 8, is a strong one indeed. Fluoride is preferred by a minimum of 10^{12}, and as high as 10^{27}, when compared to I^-. This preference is enhanced as O atoms are added to the thiophene S, and is most marked for the Ge receptors.

There were numerous reasons for selecting the M06-2X functional. In the first place, it has been tested and found successful repeatedly in applications of noncovalent interactions [85]. The latter included halogen bonds [86,87], and even anionic systems [88] not entirely unlike those considered here. Other types of related systems for which it has found good success include HBs [89-95], both neutral, and those involving an anion [96], especially pertinent here. This functional has also been subjected to wide scale extensive benchmark tests against a host of other methods and has been deemed excellent, particularly in halogen-bonded

contexts [97-103]. One study, for example, found M06-2X stacked up well against CCSD(T) data with a complete basis set [104], superior to all other DFT methods examined. Another [105] also found this functional yielded results in good agreement with CCSD(T). M06-2X appears to do very well in pnicogen and chalcogen bonded systems [106,107], of particular relevance here, even those containing an ion [108,109] as do the systems examined here. One work in particular [110] found M06-2X quite accurate when considering a tripodal perhalophenyl halogen bonding system.

In summary, the thiophene-derived receptors engage in very strongly bound complexes with the various halides. F^- is held much more tightly than are the other halides, which follow the trend $Cl^- > Br^- > I^-$. Consequently, these receptors have the potential to be used as strongly selective binding agents for F^-. The chalcogen bonds formed by the S atoms of the thiophenes are exceeded when S is replaced by the pnicogen P atoms. The pnicogen bonds are further strengthened by third-row As atoms, but the strongest complexes involve the tetrel bonds of Ge. The binding energy can be as large as 63 kcal/mol when engaged with fluoride, but exceeds 24 kcal/mol even for the larger iodide ion with its diffuse charge. The binding energy is increased when one and then two O atoms are added to the thiophene S, even though this atom is remote from the site of binding to the anion. The results presented here argue forcefully for the future testing of both pnicogen and tetrel-bonding units as elements of selective anion binding receptors.

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Table 1. Interatomic distances, R (in Å), between halide and chalcogen, pnicogen, or tetrel atom with which it interacts.

X	O0	O1	O2
F^-			
S	2.426	2.405	2.384
P	2.009/2.760	1.992/2.756	1.966/2.750
As	2.200/2.624	2.212/2.579	2.206/2.556
Ge	1.966/3.038	1.971/2.975	1.975/2.920
Cl^-			
S	3.095	3.056	3.038
P	3.168	3.133	3.072
As	3.087	3.065	3.027
Ge	3.002	2.975	2.949
Br^-			
S	3.324	3.276	3.253
P	3.467	3.425	3.324
As	3.310	3.284	3.244
Ge	3.229	3.197	3.169
I^-			
S	3.604	3.556	3.539
P	3.800	3.734	3.661
As	3.605	3.598	3.540
Ge	3.557	3.522	3.500

Table 2. Binding energies (kcal/mol) for complexation reactions

X	O0	O1	O2
F^-			
S	-29.06	-37.94	-42.32
P	-36.06	-45.78	-50.68
As	-40.56	-49.32	-53.91
Ge	-50.67	-59.94	-63.35
$2(H_2O)$[a]	-50.62		
Cl^-			
S	-12.07	-19.18	-22.35
P	-16.62	-24.46	-27.88
As	-19.42	-26.81	-30.25
Ge	-24.41	-31.66	-35.20
$2(H_2O)$[a]	-30.69		
Br^-			
S	-9.57	-16.17	-19.08
P	-13.97	-21.29	-24.23
As	-15.97	-22.95	-26.02
Ge	-19.94	-26.74	-29.95
$2(H_2O)$[a]	-27.44		
I^-			
S	-7.15	-13.20	-15.83
P	-11.35	-18.10	-20.49
As	-12.57	-19.05	-21.67
Ge	-15.41	-21.62	-24.46
$2(H_2O)$[a]	-21.24		

[a]binding energies are evaluated in reference to the uncomplexed trimer X^- + HOH + HOH

Table 3. Free energy changes (ΔG, kcal/mol) for complexation reactions

X	O0	O1	O2
F^-			
S	-21.19	-29.67	-34.16
P	-27.69	-37.02	-41.79
As	-32.47	-42.03	-45.61
Ge	-42.63	-51.58	-54.96
2(H_2O)	-33.67		
Cl^-			
S	-5.05	-11.77	-14.97
P	-9.00	-17.10	-19.97
As	-11.82	-19.16	-22.48
Ge	-17.10	-24.04	-27.95
2(H_2O)	-14.00		
Br^-			
S	-3.23	-9.49	-12.16
P	-6.51	-14.32	-16.71
As	-8.45	-15.45	-18.54
Ge	-13.01	-19.31	-22.83
2(H_2O)	-11.18		
I^-			
S	+0.68	-6.75	-9.42
P	-4.62	-10.74	-13.41
As	-4.90	-11.45	-14.40
Ge	-8.46	-14.09	-17.13
2(H_2O)	-6.86		

Table 4. Equilibrium constants favoring binding of halide to receptor versus pair of water molecules

X	O0	O1	O2
F^-			
S	6.5E-10	1.1E-03	2.3E+00
P	4.0E-05	2.9E+02	9.5E+05
As	1.3E-01	1.4E+06	6.1E+08
Ge	3.9E+06	1.5E+13	4.7E+15
Cl^-			
S	2.6E-07	2.3E-02	5.2E+00
P	2.1E-04	1.9E+02	2.5E+04
As	2.5E-02	6.3E+03	1.7E+06
Ge	1.9E+02	2.5E+07	1.9E+10
Br^-			
S	1.4E-06	5.7E-02	5.3E+00
P	3.7E-04	2.0E+02	1.2E+04
As	9.8E-03	1.4E+03	2.6E+05
Ge	2.2E+01	9.6E+05	3.8E+08
I^-			
S	2.8E-06	8.3E-01	7.7E+01
P	2.2E-02	7.2E+02	6.6E+04
As	3.6E-02	2.4E+03	3.5E+05
Ge	1.5E+01	2.1E+05	3.6E+07

Table 5. NBO values of charge transfer energy E(2), in kcal/mol, from lone pairs of halide to σ*(X-C) antibonding orbital

X	O0	O1	O2
F^-			
S	9.57	13.18	13.98
P	61.13[a]	56.62 [a]	64.05 [a]
As	47.73 [a]	45.35 [a]	45.90 [a]
Ge	59.10 [a]	57.78 [a]	56.77 [a]
Cl^-			
S	5.46	5.98	6.32
P	6.39	6.98	8.52
As	12.09	12.52	14.01
Ge	16.80	17.61	18.59
Br^-			
S	4.02	4.49	4.82
P	3.51	4.13	5.89
As	9.50	9.91	11.25
Ge	13.99	14.94	15.89
I^-			
S	2.88	3.15	3.38
P	2.20	2.69	3.51
As	6.75	6.58	7.89
Ge	9.51	10.23	10.74

[a] asymmetric

Table 6 Changes in X-C bond length resulting from formation of the indicated complexes, Δr(X-C) in mÅ

X	O0	O1	O2
F^-			
S	7.3	9.5	10.1
P	81.7 [a]	65.8 [a]	58.5 [a]
As	245.0 [a]	89.1 [a]	87.7 [a]
Ge	169.5 [a]	163.6 [a]	162.2 [a]
Cl^-			
S	-1.1	0.7	0.9
P	9.4	7.0	6.6
As	30.3	28.9	29.0
Ge	54.7	54.1	55.4
Br^-			
S	-1.9	-0.2	0.1
P	5.6	2.9	3.3
As	24.7	23.7	23.6
Ge	45.2	44.9	45.9
I^-			
S	-2.1	0.0	-0.2
P	7.7	-0.2	0.5
As	19.9	17.9	18.0
Ge	35.4	35.1	35.6

[a] asymmetric

Table 7. Electrostatic potential (kcal/mol) at $V_{s,max}$ of binding site

X	O0	O1	O2
S	17.09	26.03	30.22
P	14.28	24.66	29.80
As	15.94	25.37	30.35
Ge	22.50	30.82	35.15

Table 8. Equilibrium constants favoring binding of F^- to receptor over indicated halide

X	O0	O1	O2
Cl^-			
S	7.6E+11	1.5E+13	1.3E+14
P	5.7E+13	4.6E+14	1.1E+16
As	1.6E+15	6.8E+16	1.1E+17
Ge	6.2E+18	1.9E+20	7.6E+19
Br^-			
S	1.7E+13	7.1E+14	1.6E+16
P	3.9E+15	5.1E+16	2.9E+18
As	4.8E+17	3.7E+19	8.4E+19
Ge	6.3E+21	5.7E+23	4.5E+23
I^-			
S	1.3E+16	7.4E+16	1.6E+18
P	9.6E+16	2.2E+19	7.7E+20
As	2.0E+20	3.2E+22	9.4E+22
Ge	1.4E+25	3.9E+27	7.0E+27

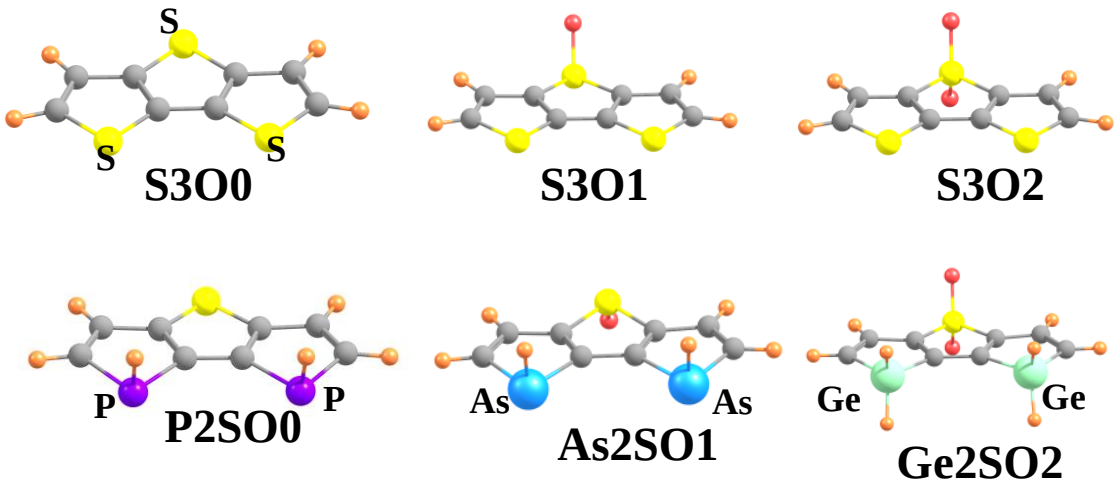

Fig 1. Geometries of selected receptors, indicating notation convention.

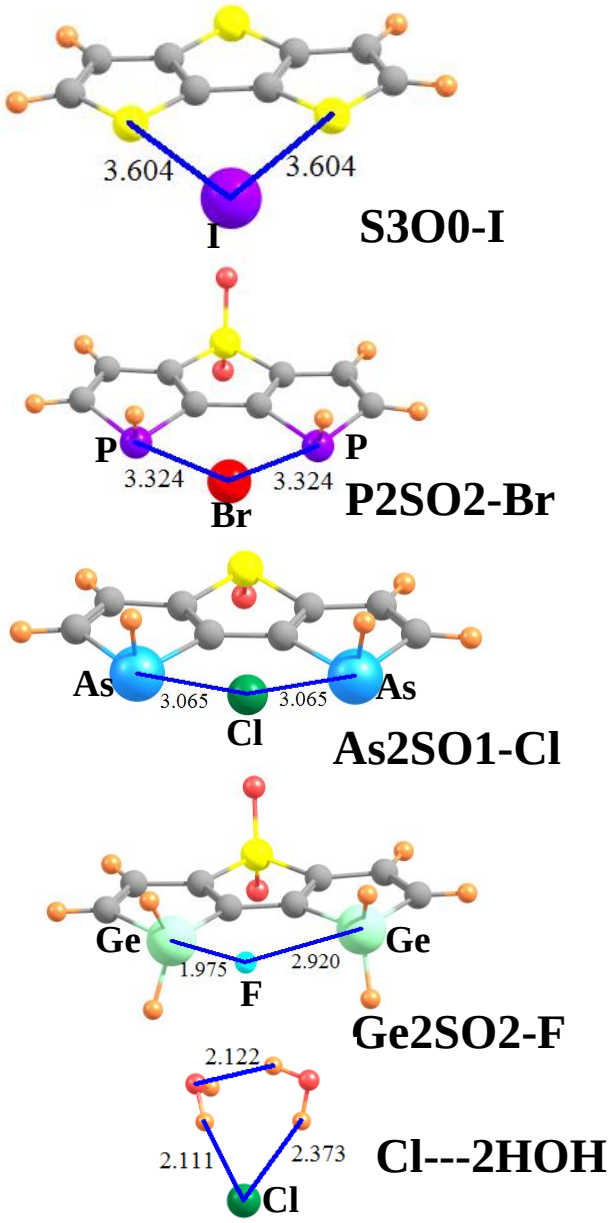

Fig 2. Geometries of selected receptor/halide pairs. Interatomic distances in Å.

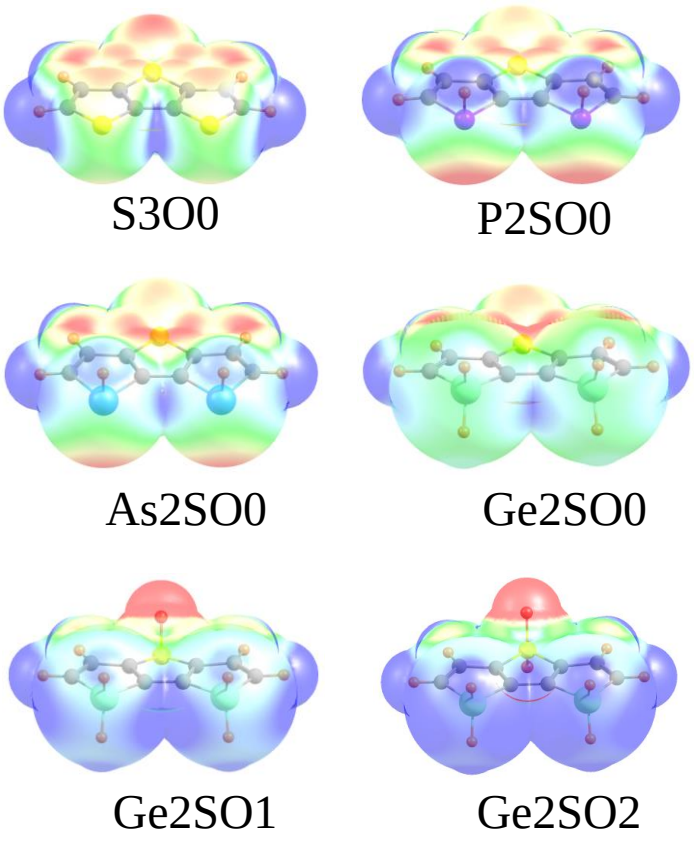

Fig 3. Molecular electrostatic potentials (MEPs) of indicated receptors. Blue color refers to a value of +0.02 au on the surface corresponding to 1.5 times the van der Waals radius of atoms, red represents a negative potential of -0.02 au.

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